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The New Trends in Next Generation Biomimetics Material Technology: Learning from Biodiversity

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1 Introduction

1-1 Monozukuri Technology Inspired by Nature

The importance of "Learning from Nature" is a prevailing knowledge in each field of science and technology. Since the turn of the century, the research and development on the nature-inspired manufacturing technology, generally referred to as "biomimetics," have been coming to the fore in Europe and the United States. For example, National Geographic Magazine put together the feature stories on "Nature-inspired Design" in its April 2008 issue. It presented, under the title "Biomimetics: Design by Nature," a variety of research and development projects now in progress, such as the fluid-dynamically fuel-efficient car design and the paint that can be cleaned by rain. Some of the contents of these feature stories were presented in detail in Peter Forbes' book "The Gecko's Foot: Bio-inspiration—Engineering New Materials from Nature" published in 2005 (Japanese translation by Michiyo Yoshida was published from Hayakawa Publishing Corporation in 2007). More recently, the importance of "Learning from Nature" is recaptured from the viewpoint of energy and environmental concerns. For example, in 2008 the incorporated nonprofit organization Biomimicry Institute hosted a conference titled "Biomimicry's Climate-Change Solutions: How Would Nature Do It?" This NOP was established by Janine Benyus, the author of "Biomimicry: Innovation Inspired by Nature" (Japanese translation by R. Yamamoto and M. Yoshino was published by Ohmsha Ltd. in 2006). The concept of "Nature's 100 Best" (Innovation Inspired by Nature) propounded by them has been gaining attention, and presented both in COP9 (The 9th meeting of the Conference of the Parties of Convention on Biological Diversity) held in Bonn in 2008 and the UNEP (United Nations Environmental Programme) held in 2009.[NOTE 1] The details of "Nature's 100 Best" is presented at ZERI Foundation (Zero Emission Research Initiative Foundation)'s website.[NOTE 2]

The terms such as "biomimicry," "bioinspiration," and "bioinspired" are derived words from "biomimetic," and, as is described later, "bioinspired" is sometimes used to connote a presumed heir of the word biomimetic. In this article, however, "biomimetic" is consistently used as it is the origin of these words and has comprehensive meanings.

1-2 Growing Interest in Biomimetics

In the backdrops of the growing interest in nature-inspired manufacturing, there has been a "changing tide" of biomimetics research that is rapidly developing and forthcoming across the period spanning from the end of the previous century to the current century. According to ISI Web of Knowledge, the number of papers relating to biomimetics has shown a steep increase since the turn of the century (See Fig.1).

A journal specializing in this field "Bioinspiration & Biomimetics" came out in 2006, and major academic journals such as PNAS[NOTE 3] and MRS [NOTE 4] had feature issues on biomimetics. The number of international conferences relating to biomimetics is steadily on the rise. The National Academies (U.S.) has taken up biomimetics as one of the challenges to be addressed, and issued in 2008 a proposal for the science and technology policies entitled

[NOTE 1] UNEP:United Nations Environment Programme
[NOTE 2] ZERI:Zero Emission Research and Initiative
[NOTE 3] PNAS:Proceedings of the National Academy of Sciences
[NOTE 4] MRS:Materials Research Society

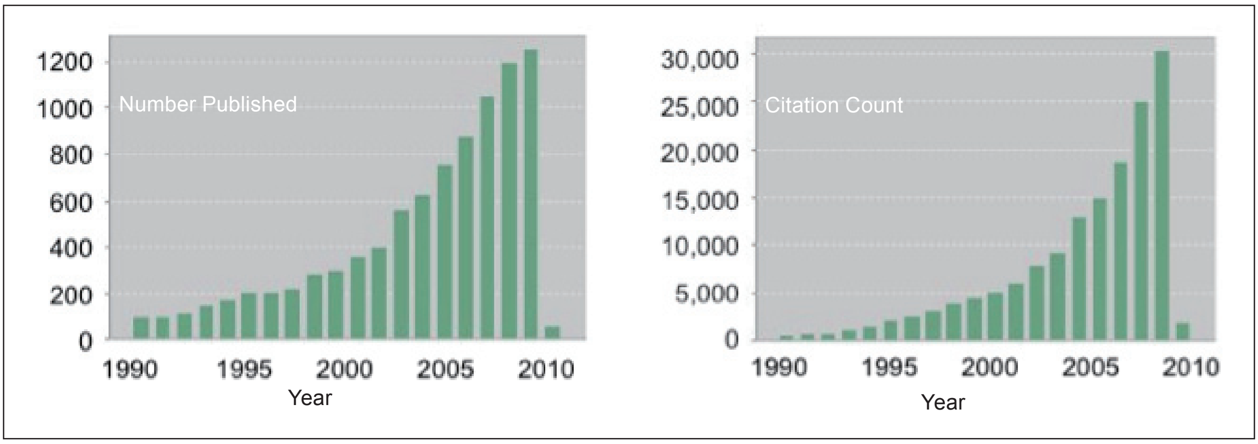

Figure 1 : Trend of Published Papers in Biomimetics and Related Fields

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"Inspired by Biology: From Molecules to Materials to Machines," wherein super water-repellent surface materials that mimic lotus leaves, adhesives that mimic gecko fingers, and photonic materials inspired by Morpho butterflies are presented as examples of "Next-Generation Bioinspired Materials." In view of promoting academic-industrial alliances and industrialization in this field, a full-scale international convention, "International Industrial Convention on Biomimetics," is scheduled to open in Berlin in March 2011 under the auspices of the Federal Republic of Germany.

2 History of Biomimetics Research

Why has biomimetics research, with its long history, been regaining attention as a new trend since the turn of the century? Figure 2 gives an overview of the history of biomimetics research from the viewpoint of the sizes of research objects and fields of interests.

2-1 The Dawn of Biomimetics Research

The term "biomimetics" (in Japan, the term is translated literally as "Imitation of Living Things") was proposed by German-American neurophysiologist Otto Schmitt in the latter half of the 1950s.[1] Schmitt is known as the inventor of the Schmitt trigger, which

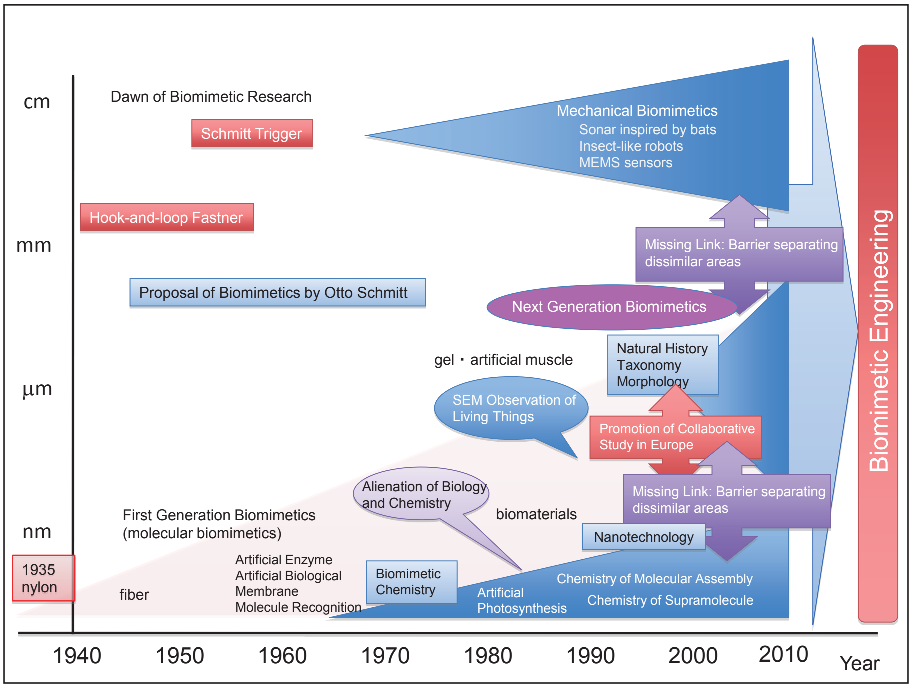

Figure 2 : History of Biomimetics Research

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is an electric circuit used to eliminate superimposed noise from an input signal and transforms it into a series of rectangular pulses. This invention was an example of simulating signal processing taking place in the nervous system. The biomimicry approach in material research dates back further: VELCRO® (known as “magic tape” in Japan) is considered to be an early example of biomimicry realization, and the light-reflecting plate embedded in the center line of roads (raised marker, or “Cats Eye”) is also said to be an exemplification of biomimicry technology.

2-2 Appearance and Decline of Biomimetic Chemistry: The First Generation Biomimetics Research

In the 1970s, biomimetics research came along in the fields of chemistry, as “Biomimetic Chemistry,” aiming at molecular-level emulation of enzymes and biomembranes. Around the same period, it became apparent that the X-ray structural analysis had the capability to provide reaction site information on enzymes (i.e., biocatalysts), enabling molecular-level elucidation of biological reactions using techniques of organic chemistry. What was essential in unraveling biological events from chemical standpoints in view of engineering applications was the biology-chemistry collaboration. The artificial photosynthesis research that became active in the 1980s laid the foundation for dye-sensitive solar cells, and the actuator research, using gel, brought about such inventions as synthetic muscles.

However, the evolution of molecular biology subsequently turned the mainstream of biology toward the elucidation of life phenomena, where the gene plays a central role. The mainstream of biomimetic chemistry research—an area best described as “biomimetics of molecular systems”—began to show tendencies, accompanied by the rise of molecular electronics research in the latter half of the 1980s, to distance itself from biology, and headed toward the chemistry of molecular assemblies and supramolecules. Entering the 1990s, in spite of the prevalence of the idea “Learn from Living Things,” the opportunities for linkage with biology, in effect, almost disappeared. Even the term “Biomimetic Chemistry,” which represented an academic field, became almost extinct in the wake of the shift of focus toward molecular nano-technology and nano-biology. The idea “bioinspired —taking cues from living things and surpassing them—became mainstream, marking the decline of the first generation biomimetics, or biomimetic chemistry.

2-3 The Development of Mechanical Biomimetics

In the 1970s, biomimetics research also blossomed in such fields as mechanical engineering and fluid dynamics; developments in these fields included robots that mimicked movement of insects and fish, and the sonars and radars that mimicked echolocation capabilities of bats and sensory hairs of insects. Mechanical biomimetics research has continued without decline up to now mainly in such areas as military industries, railways and ships, and aeronautics industries. They have also had an impact on such cutting-edge fields as micromachines and MEMS.[NOTE 5] In present-day Japan, the term “biomimetics” seems to have more of a connotation synonymous with robotics research.

2-4 The Rise of Material Biomimetics

As exemplified by the proposal made by the National Academies (U.S.) in 2008, i.e., “Next-Generation Bioinspired Materials,” with the coming of a new century, new trends of biomimetics have been gaining focus in material research centered in Europe and the United States. A movement is afoot to bring the research results into practical use.

In many cases, the surfaces of living things are characterized by hierarchical structures in dimensions ranging from nanometers to micrometers. These ranges of dimension are the targets of nano-technology. One of the outstanding characteristics of nano-technology, as compared with conventional technologies, is the fact that its objectives have dimensions that require observation and analysis using electron microscopy, and this very fact embraces possibilities to provide a platform for biology-material science collaborations through the use of common methods for observation and analysis. Electron microscopy has revealed the hierarchical structures of living things that range from nano- to miro-meters range. Inspired by the knowledge of the hierarchical structures in the surfaces of living things, as revealed by the researchers of morphology and taxonomy, the development of nano-technology in the last decade has enabled the material researchers to artificially

[NOTE 5] MEMS:Micro Electro Mechanical Systems manufacture similar structures and they are in the process of artificially realizing functions that originate from the structure. Researchers in Europe, especially Germany and the U.K., have been the driving force of these researches.

As described earlier, the first generation biomimetics, or Biomimetic Chemistry, was born thorough a collaboration between biology and organic chemistry that aimed at mimicking living things on the molecular level, and X-ray structural analysis built a momentum for this trend. In contrast, the material research, or new generation biomimetics, are considered to have been created through collaborations among natural history, biology, and material nano-technology, where electron microscopy and microfabrication technology provided the common platform. The characteristics of nano-technology in Europe are symbolized by the term “Nano meets Bio.” That is, the objective is the fusion and linkage between dissimilar fields. For example, in the research carried out in German universities, linkage between dissimilar fields has become the prerequisite for gaining research funding.[2] The reason that signs of forthcoming activities in new generation biomimetic material research appeared first in Europe can be ascribe to a cultural background that values cross-fertilization as well as to the European science and technology policies that proactively look to fusing together dissimilar fields.

3 Trends in the Research of Next Generation Biomimetics Materials

In this chapter, some of the success stories of biomimetic material research are presented. These challenges have their sights set on practical applications and the description is centered on how the collaboration between biology and material nanotechnologies was carried out.

3-1 The Superhydrophobic Material Inspired by Lotus Leaves, and the Research Derived from It

The wettability of a solid surface with water is governed by the material’s intrinsic degree of hydrophilic/hydrophobic property (surface free energy) and surface profile. In general, such materials as silicone, wax, and fluoride compounds have a low level of surface free energy, and show hydrophobic properties because of the poor hydrophilicity. A hydrophobic surface with rough surface irregularities has an augmented actual surface area (Wenzel state), and the small void formation due to the surface irregularities hinders water from entering (Cassie-Baxter state). This makes the surface even more resistant to wetness.[3]

Professor Wilhelm Barthlott (a botanist at the botanical garden in Bonn University) found that, on the surface of lotus leaves, the surface microstructure and secretion of wax-like compounds have a synergetic effect that produces superhydrophobic property and is self-cleaning.[4] Arrays of bumps the size of several micrometers are found on the surface of lotus leaves, and, protrusions of microcrystals made of wax-like material form arrays on the surface of each bump. The fractal undulating structure, with the hierarchical structure described above, provides the surface of lotus leaves with such super hydrophobic property.

Surface microstructure brings about hydrophobicity, resulting in a cleaning effect, which is called the Lotus-Effect® (a trademark of Bonn University). Bonn University carried out collaborative research with a plural of companies and developed a paint called “Lotusan”—nanoparticles (e.g., hydrophobic silica) are dispersed in a binder material. Several companies including Evonik (former Degussa) have put the paint into commercial production. The discovery of the lotus effect can be counted as one of the most classical successes in new generation biomimetics research, and it was brought about by biology-material science-industry collaborations. Inspired by this success, cases of technological developments are underway in search of effects similar to Bonn University’s. These include the textile spray (MincorR TX TT, BASF), coating material (Nikka Chemical), hydrophobic polymer (Lexan, GE), convexo-concave surface formation by means of plasma CVD technique (Nagoya University), and highly water-resistant cosmetics (Kanebo).

The discovery of the lotus effect induced surface-structure research on living things that dwell in aquatic environments. The petals of roses, clivias, and sunflowers show superhydrophilicity, but at the same time they have so strong an adsorption power to water that they hold water drops even if they are held upside down. Rose petals, as well as the surface of lotus leaves, have hierarchical structures, and the surface of bumps (10–20μm) is covered, not by the protrusions, but by the concatenation of pleats with the repetition period of several hundred nanometers.

These pleats are considered to be the source of strong adsorptive power,[5] and they originate from van der Waals force inherent to the microscopic surface structure. Synergetic coexistence of hydrophobicity and adsorptivity is called the “rose petal effect,” and the polystyrene nanofiber with its hollow structure represents a material that exhibits this effect.[6]

The materials covered by dissimilar patches of surfaces—ones with hydrophobicity and others with hydrophilicity—were also developed through a collaboration of biologists and material scientists. Professor Andrew Parker (a biologist at London’s Natural History Museum) studied the Stenocara gracilipes—a beetle inhabiting in Namib Desert—and elucidated the mechanism the beetle uses to drink water by gathering tiny water drops of morning dew. Living in the desert near the sea, the beetle stands straight for a while with its head down every morning and evening. Its body surface is covered with a patchwork of dissimilar surfaces—tiny hydrophobic bumps the size of micrometers, and hydrophobic patches in between that are one-tenth the size of the bumps and characterized by a convexo-concave structure. The dewdrops adsorbed in the hydrophilic surface patches gradually grow, their weight causes them to roll down along the hydrophobic surfaces, and they gather into the mouth of the beetle standing with its head down.[7] Professor M. Rubner and R. Cohen at Massachusetts Institute of Technology developed water-gathering material that mimicked these beetle surface skins. They used a thin-layer manufacturing technique called the Layer-by-Layer method to develop water-repellent property, an array of silica microparticles (hydrophilic bumps) on a solid substrate, and the area in between was covered by water-repellent fluoride compounds. Dews are trapped and grown to water drops on the surface of silica particles (hydrophilic adsorption sites) and these were successfully gathered into one location through the channels formed by the surrounding water-repellent smooth surface.[8] They consider it probable that a scaled-up version of this type of surface could be used as a device for dew collection, to secure water resources in dry regions and areas with poor fluviatic resources.

As described later in section 4-6, the manufacturing techniques also present major research challenges in the development of biomimetic materials. Among them, the self-organization technology has become a focus of attention. An attempt has been made to make a surface material that is both superhydrophobic and strongly adsorbing by actively introducing adsorbing sites in the water-repellent surface using the self-organization phenomena and a simple electroless plating technique. A polymer spike—metallic microdome composite—was manufactured. This material is characterized by the coexistence of superhydrophobicy (due to polymer spikes) and strong hydrophilicity, allowing a large contact angle and giving strong absorptive power to the water drops that came in contact with it.[9] That is, this material was created by a combinational approach involving biomimetic material design and a manufacturing technique employing self-organization. In addition, incorporation of a metal for additional functions made it a hybrid material.

In recent years, China has had a brilliant track record in research and development of biomimetic superhydrophobic materials. The researchers in China are trying to find an interrelation existence between the various types of surface structures of living things and their functions. These include the oil-repellent property of fish scales, water-collecting material inspired by spider webs, and water-repellent property inspired by mosquito eyes, butterfly wings, and legs of water striders.[10]

3-2 Growth of Material Development Inspired by Sharkskin Riblet

The “swimsuit row” that involved people concerned in competitive swimming in 2008, just before the Beijing Olympics, was, from the point of view of material development, a major accomplishment for Speedo’s biomimetics strategy—although it was accused of being “high-tech doping” in some quarters. Speedo’s LZR Racer®, and its prototype FASTSKIN-FSII®, achieved high-speed swimming by using a hollow-fiber textile, in addition to the weight saving accomplished through superhydorphobic treatment. It was a verified knowledge that a water-repellent surface had a resistance mitigating effect to laminar flow, and it was theoretically predicted that it had a similar effect to turbulent flow as well. One characteristic of Speedo’s swimsuits that attracted attention was the fact that they had a fish-skin riblet structure on their surfaces. The riblet structure is characterized by repetitive grooves in several tens of micrometers to below one-millimeter intervals,

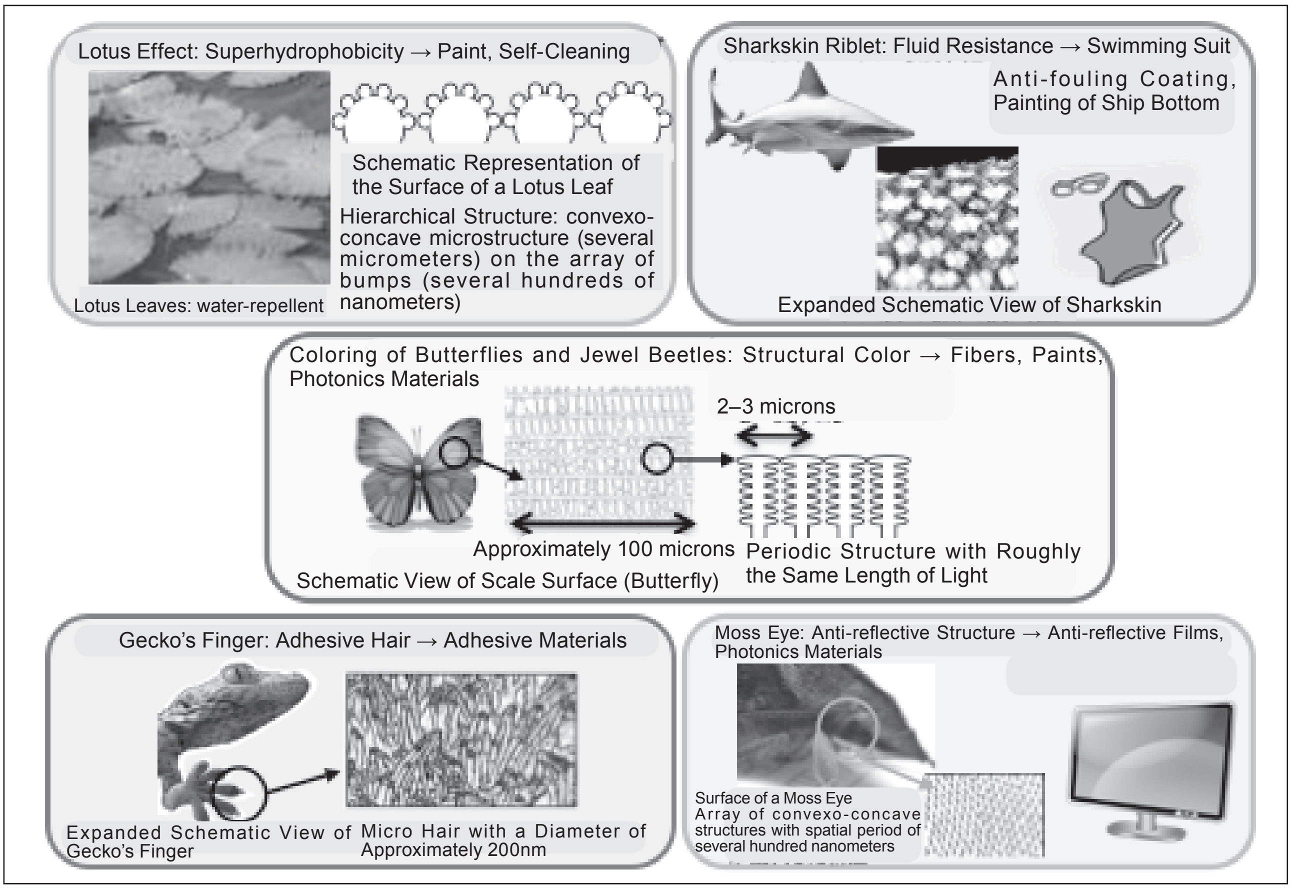

Figure 3 : Success Examples of New Generation Biomimetics Material Research

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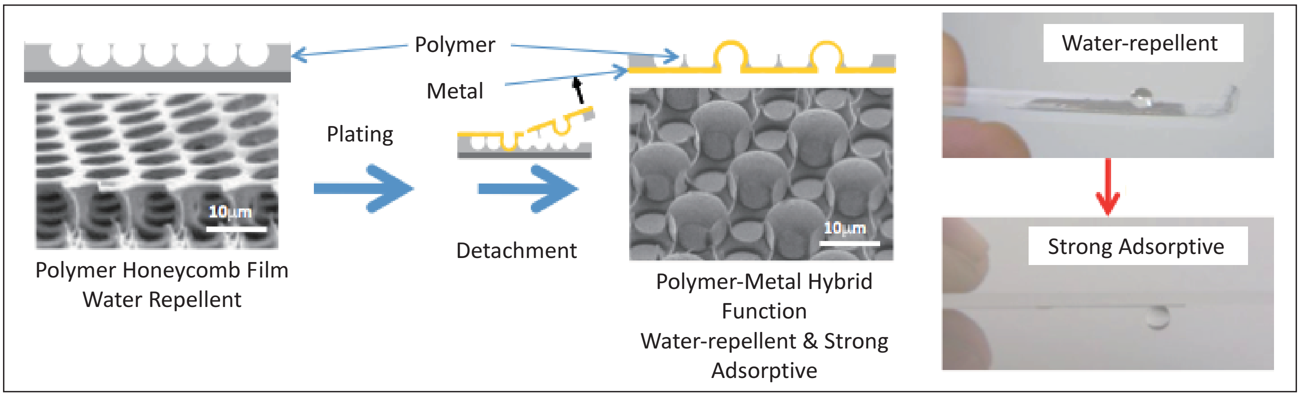

Figure 4 : Example of Biomimetics Material That Incorporates Self-Organization

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and the introduction of such structure had been long known to reduce friction resistance with a fluid. The riblet films developed by 3M have been applied to the outer surfaces of racing yachts (e.g., America's Cup) and Airbus industries' passenger aircrafts, and they have been reported to have improved cruising velocity by several percents and enhanced fuel efficiency.

In recent years, the riblet structure has also attracted attention for its anti-fouling effect. The conventional method of choice to deter attachment of marine organisms (i.e., acorn shells and algae) to the ship bottoms and cooling water channels of power plants has been the use of TBT (tributyltine). However, because TBT is one of the hormone-disruptive substances (so called "environmental hormone"), the International Maritime Organization decided to make a blanket ban to be implemented by 2008. Therefore, TBT-free anti-fouling methods, especially an effective use of surface structure, are under investigation. Solid surfaces with surface tension in the range between 25 and 0 mN/m are known to have a physical effect to hinder biofouling. A research group at Hochschule Bremen reported that a surface made of soft silicone with a riblet structure on it (riblet interval: 76μm, surface tension: 25mN/m) had an effect of reducing nearly 70% of an acorn shell attachment as compared to a flat and smooth surface.

In another development in Europe, "Surface Engineering for Antifouling—Coordinated Advanced Trainin (SEACOAT)" started in January 2010 as one of the European Frame Work Programs (FP7). As part of this program, a joint effort between industries and academia aiming at the anti-fouling material development utilizing nano-/micro-structure has started. The multi national research team consists of 17 organizations from countries including the U.K., Germany, and Switzerland.[11]

In recent years, the riblet structure has attracted attention in applications other than marine anti-fouling. Professor Anthony Brennan at Florida University and other researchers have focused attention on the antibacterial properties of the riblet structure. They developed a medical film (Sharklet TM) and aim to use the film in such applications as the wall material of medical facilities and medical devices such as catheters.

The website of the National Museum Director's Conference (U.K.) states that the sharkskin riblet was an accomplishment of joint-research with the museum for the 2008 Olympic games, and it reduced fluid resistance by three percent. Fiona Fairhurst, a Speedo's "Biomimetician" and the developer of FASTSKIN®, was recommended as a candidate for the European Inventor of the Year Award in 2009, and she expressed her appreciation to the members of London's Natural History Museum for their corporation. This is a symbolic episode indicating that the collaborations between natural history and nanotechnology are absolutely necessary for the new generation of biomimetics research and development.

3-3 Structural Color Materials Inspired by Butterflies and Jewel Beetles: Database Compilation of Relevant Information

The body color of jewel beetles and morphos, with characteristic metal luster, is called a "structural color." Structural colors develop their peculiar tints not through light absorption by pigments or colorants, but by a microstructure with the dimensions comparable or shorter than the wavelength of light. Therefore, structural colors are free from such problems as fading and degradation. A variety of mechanisms is known to be the sources of structural color expression: thin layer interference, multilayer interference, interference caused by micro-scale grooves and bumps, and scattering and diffraction of light caused by arrays of microparticles. Material development research inspired by structural color expression of living things are actively underway: collegiums on structural color are being held under the leadership of Professor Pete Vukusic at the physics department of Exeter University (U.K.) and Professor Shuich Kinoshita at Osaka University (Japan), and these provide useful information regularly on this subject. Structural color also presents itself, other than on the body surface of living things, in minerals (e.g., opal) and colloidal crystals. The applications of structure color cut across a variety of industrial sectors, including paint, cosmetics, jewelry, textiles, and photonic crystals. The structural colored fiber morphotex is a world-renowned accomplishment, and was developed through the collaboration of three companies: Nissan Motors Co., Ltd, Teijin Fibers Ltd., and Tanaka Kikinzoku Kogyo. Recent research has further pointed out potential use of high-refractive index organic materials for structural color expression.[12]

Professor A. Parker and et al at London's Natural History Museum published the paper "The reviews on diversity and evolution of butterfly's photonics structures, with mentions to the achievements done by John Huxley" in the Proceedings of the Royal Society.[13] They considered that the anatomic and comprehensive descriptions of the photonic structures of butterfly wings would contribute to potential applications of biomimetics, and compiled the review based on the unpublished electron micrographs taken by the late Dr. John Huxley as a useful database to understand diversity and evolution. The publication of the vast amount of inventory stored in the museum (a catalog of all living things inhabiting a region, and investigation results for making such a catalog) and the compilation of the data into a database, from the viewpoint of anatomical structures and functionality, was a worthwhile endeavor for the next generation biomimetics research.

3-4 Adhesive Materials Inspired by Gecko Legs

The biomimetics of gecko lizards' fingers have been, as well as the lotus effect, another success stories of biology-material science collaboration. In June 2003, BBC News (online) published the article "Gecko inspires sticky tape," about a research group, headed by Professor Andre Geim at Manchester University, that successfully developed an adhesive-free adhesion tape that mimicked the microstructure of a gecko finger. It is a wonder that a gecko can crawl on walls and ceilings considering that it does not secrete a sticky substance on its fingertips. A gecko's fingertips have traces of cracks (lamellars) and thick growth of several hundreds of thousand of bristly hairs (seta) inside the cracks. At the tip of each bristly hair, with a length around 100μm and diameter around 5μm, the hair ramifies into several hundreds of split ends, with a dish-like structure (spatula) on each end. Each spatula has an approximate diameter of 200nm. According to the biological hypothesis of Keller Autumn et al,[14] the adhesive force of the gecko fingertips originates from van der Waals force between the surfaces of the dense growth of hierarchically structured microscopic bristly hairs and the wall surface. The research groups of Ronald Fearing at UC Berkley[15] and Andre Geim[16] reconstructed a surface with a dense growth of bristly hairs on it, whereby a microfabrication technique using AFM (Atomic Force Microscopy) chips and the nanoscale pores of anodized alumina was used. They not only elucidated the adhesion mechanism of gecko fingers, but also succeeded in developing an adhesive-free adhesion material (i.e., "Gecko Tape"). Subsequently, a paper reported that the solid surface with its dense growth of bristle hair made of carbon nanotube also exerted a strong adsorptive power.[17] Research and development efforts toward practical use of this technique have already begun, and the objectives include an adsorbent agent used in recyclable construction materials. A gecko-type robot capable of moving along walls has been developed. It uses a gecko tape as an adsorptive agent and is expected to have a range of applications in both civilian (such as disaster-relief operations) and military uses.[18] Currently, the efforts toward practical use of this type of robot are being stepped up notably in the United States.

3-5 Anti-reflective Materials Inspired by the Moss-eye Structure

In the 1960s, C. G. Bernhard et al (Karolinska Institute, physiological department) reported that the surface of a moth's compound eye is covered with arrays of protrusion structures approximately 100nm in size.[19] Subsequently, in the early 1980s, S. J. Wilson, M.C. Hutley, et al (optics division of U.K. National Physics Laboratory) made clear that a periodical array of convexo-concave structures (moth-eye structures) had the effect of gradually changing refractive index in the direction normal to the surface, resulting in a non-reflective surface.[20] This structure, in effect, eliminates the clearly defined reflecting plane (step change of refractive index) and suppresses light reflection. The complex eye with such internal structure enables the moth to fly at night, and, because the light reflection from their large eyes is suppressed, is believed to hinder predators (e.g., birds) from finding them.

The anti-reflective film, with its moth-eye structure, received attention from early on in the research and development of optical materials. Holotools GmbH (Germany) used the interference lithography technique to produce repetitive patterns with the period from 100nm to 100μm on a solid substrate. Using this technique, the company manufactures transparent polymer films with their surfaces covered by the moth-eye structure, and provides the product for use as a large-area anti-reflective film of a display device. Recently, Mitsubishi Rayon Co. Ltd. succeeded in incorporating moth-eye structure on the surface of a transparent polymer film (the commercial product has reflectance below 0.1%, and total transmission of 99.6%), whereby anodized alumina—nanoscale pores are formed regularly in self-organized fashion—was used as a die. In 2009, Oji Paper Co. Ltd. succeeded in establishing the technique to coat a surface on which a single layer of microparticles (25–1000nm in diameter) are being arrayed in high precision, and this led to a successful manufacture of the dot-type periodic microstructure.

The moth-eye structure also gains attention from a viewpoint of enhancing solar cell efficiency.[21] J. G. Rivas et al (Institute for Atomic and Molecular Physics (AMOLF), the Netherlands) discovered that a fabrication of moth-eye structure rods on the surface of a GaP substrate drastically reduces the wide wavelength range of light reflection (from visible to near-infrared region). In Japan, Mitsubishi Electric Corporation has achieved 18.6% of photoelectric conversion efficiency in its polycrystalline solar cells: to reduce surface reflectance, a honeycomb convexo-concave structure was introduced on the surface of the polycrystalline silicone solar cells using laser patterning and wet etching techniques. Mitsubishi plans to put it to practical use in 2010.

3-6 Low Friction Materials Inspired by Sandfish

Scincus scincus, a lizard that belongs to Pholidota skinks, is an inhabitant of deserts in North Africa and Southwest Asia, and is called a "sandfish" as it dives into the sand and moves below the surface in a swimming-like motion. It is around 15cm in length, goes under the "sea of sand" to the depth of several centimeters, and it can "swim" at a speed of 10–30cm/sec.[22] Professor Ingo Rechenberg at Berlin Institute of Technology found that the sandfish's scaled skin had a even smaller friction coefficient than those of polished steel, flat and smoother glass, Teflon, and high-density nylon surfaces, and showed hardly any sign of wear after it suffered abrasion with sand. The scales of a sandfish consist of sulfur-rich glycosylated ceratine, and do not contain inorganic materials such as silicates. Having ceratine as the main component, the scales have microstructures on their surface and these produce peculiar tribological properties. Professor W. Baumgartner et al coated a polymer film with the ceratine extracted from the scales, and found that the surface showed similar properties as the scales. Using atomic force microscope measurements, they showed that there is hardly any attractive force between the surfaces of the scales and a silicon chip. Rechenberg et al verified that the falling angles of sand on a sandfish skin are lower than those on glass, nylon, Teflon, and steel surfaces, which exemplified the very low frictional resistance. On the other hand, the sandfish skin has a higher abrasion resistance than those surfaces of steel and glass. The scale of a sandfish is characterized by an array of "nanothresholds" with sub-micrometer height, stretching like mountain ridges with several micrometers spacing in between. Rechenberg et al suggested that the static electricity generated by frictional electrification between the "threshold" and sand grains is the probable origin of friction reduction, i.e., the static charge produced repulsive force between the scale and sand grains. The predator of sandfish—the snake—also has a skin with a very low-friction surface, presenting an investigation object for biomimetics research.[23]

In the program "Abrasion resistant surface coating mimicking the sandfish's epidermis" under the guidance of Professor W. Baumgartner at RWTH Aachen (Germany) —included in the doctoral research and educational program called BIONIC Graduate[24] —research and development is underway to analyze chemical and physical composition of the sandfish's epidermis, and coating processes of metal, glass, and polymer surfaces using these sandfish skin components. The final objective of the program is to develop a low-cost coating technique that realizes an abrasion-resistant surface inspired by the tribological properties of the sandfish's epidermis structure. Scar-resistant front glasses and lubricant-free low friction ball bearings are among the accomplishments to be expected from the program.

Recently, X-ray footage was taken of a sandfish "swimming" in the fluidized sea of sand, undulating and snaking its body, without using the four legs. The tribological effects of the scale surface, characterized by the microscopic structure, on the sandfish's fluid dynamics while it is swimming in the "fluidized media" of fine solid particles have become steadily apparent. The research on the "swimming" of a sandfish has the potential to provide new links between the material-oriented and mechanics-oriented biomimetics.

3-7 Research on Tribology Inspired by the Evolutional Struggles between Insects and Plants

Professor Stanislav Gorb et al at Kiel University (zoological department) have been advancing systematic research on the surface tribology of insects and plants. For example, Tettigonia Viridissima (a grasshopper) has a tile-like arrangement of hexagonal patterns on the tips of its legs (see Fig. 5). Similar microscopic patterns were fabricated artificially on the surface of silicone rubber using microfabrication technology and their frictional properties were measured.[25] The results showed that the patterned surface guaranteed stable mobility in both dry and wet conditions: when the surface is dry, it enabled smooth movement completely eliminating stick-slip motions, and when wet, it had the effect of avoiding hydroplaning, or side skids.[25] As the result of undergoing evolution and adaptation in close connection with insects, some of the plants also have interesting surface mirostructures. Dr. Elena Gorb, a botanist, revealed that Sarawak's pitcher plant, a insectivorous plant, has types of mirostructures on its outer and inner surfaces,[26] making the surface quite slippery to many insects. One of the inner surfaces used to catch hold of an insect, called a slippy zone, is observed to have a structure similar to the superhydrophobic fractal structure that appears on the surface of alkyl-ketene dimer crystals[27]—a sizing agent used to modify paper surfaces. This is quite an interesting finding from a viewpoint of material science.

Evolution processes have bestowed a manifold of functions to the legs of insects. A beetle (Pameridea roridulae) can prey on a fruit fly trapped on the surface of Roridula gorgonias (a plant that secretes sticky substance) without being itself trapped by the stickum. The legs of beetles have a grease-like cuticle epithelium that can partially peel off and acts as a “sloughing-off” layer. This layer is believed to be instrumental for an insect to escape from the sticking material secreted from a plant.[28] This research has been advanced as a part of the Germany priority program “Biomimetic Materials Research: Functionality by Hierarchical Structuring of Materials (SPP 1420 priority program).”

3-8 Sensor Materials Inspired by the Sensing Ability of Insects

In recent years, the research on sensors using new biomimetic materials is being carried forward, wherein biologists are playing the central roles. Cupedidae (Melanophila) is known to deposit its eggs to a vacant ruin after a bush fire. The lack of predators is believed to induce the insect to lay eggs in the fire ruins. Cupedidae has a highly sensitive infrared sensor that can detect a bush fire several tens of kilometers away, and Professor H. Schmitz et al at Bonn University (zoological department) elucidated that it is a type of mechanosensitive sensor.[29] Multiple arrays of spherical sensory cells (sensillum) are arranged on the backs of complex eyes, and each cell has sensory hairs covered by hard cuticle walls before being connected to a neuron cell (see Fig. 6). A structure consisting of narrow canals is in place inside the cell, and the canals are filled with liquid. Irradiation of infrared light (wavelength 3μm) causes an effectively thermal expansion of the liquid inside the canal and thus compresses the sensory hairs, resulting in a conversion to mechanical stimulus that is transferred to the nervous system.

Based on these findings, Bonn University advanced a joint research with CAESAR[NOTE 7] at PMI [NOTE 6] and has developed a prototype for a robust infrared sensor that requires no cooling device. The sensor has a very simple operating principle: thermal expansion of liquid (water) confined in a tight space is detected by a condenser.

The cricket is known to have the ability to detect the approaching predator by sensing the change of airflow. The growth of aeroscepsy hairs located at the rear tail of the body is actually a sensillum array[30] (different size of sensory hairs are arranged to cover a wide frequency range) to effectively pick up a signal among noises (Fig. 7). The aeroscepsy cell of the cricket has an energy threshold comparable to the Brownian motion energy (kT), and the cell is said to have the ultimate efficiency as a sensory organ.[31] A MEMS sensor that mimics the sensory hair of the cricket is under development by a joint research team consisting of the group led by Professor J. Casas at Tours University (entomology department) and the group led by Professor G. Krijnen at Twente University (Transducers Science and Technology Group (“MicMec”)).[32]

The accomplishments from the collaborative research were presented at the international conference held in Dresden in 2009 (“1st Natural and Biomimetic Mechanosensing”). This conference was held under the initiative of the European consortium called “CILIA.”[NOTE 8] Other presentations in the international conference relating to the biomimetics of cricket included the polymer sensor film that mimicked the cricket’s eardrum.[33]

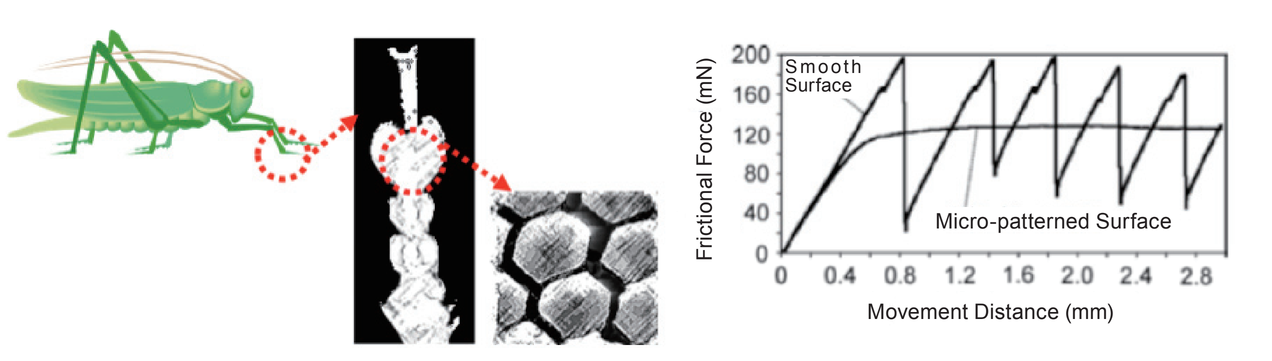

Figure 5 : Tribology of Insects’ Legs

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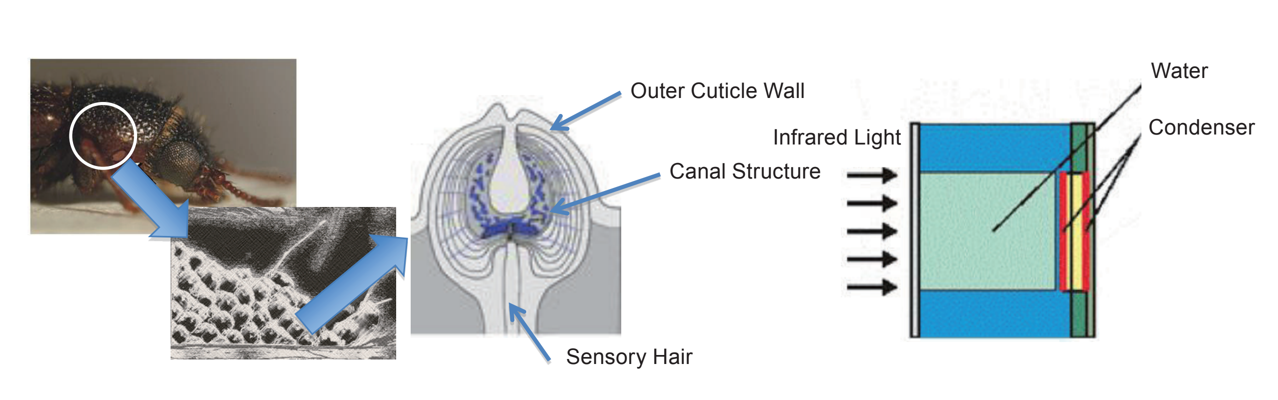

Figure 6 : Schematic Diagram of an Infrared Sensor Inspired by and Mimicking the Infrared Receptor Arrays of Cupedidae

Prepared by the STFC

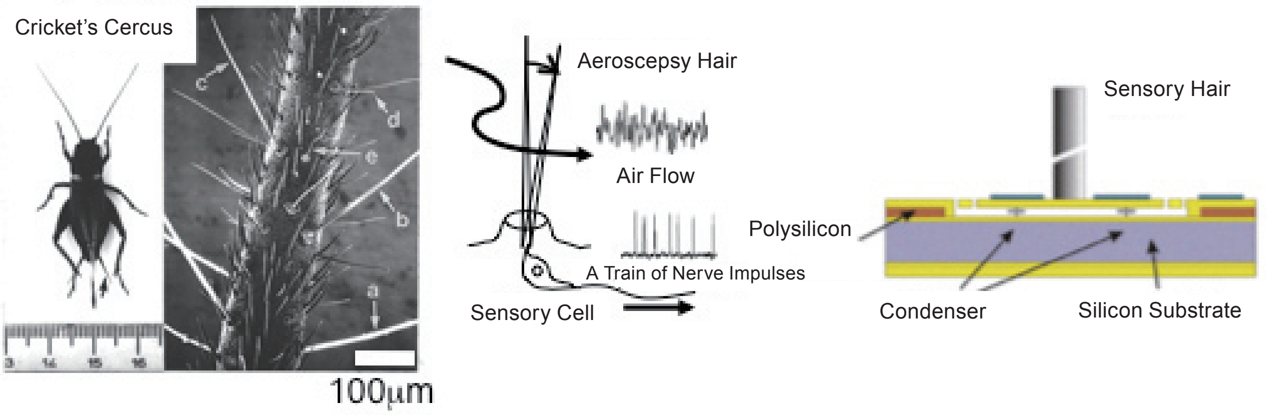

Figure 7 : MEM Sensor Inspired by the Flow Sensor of Cricket

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4 Important Points of New Generation Biomimetics Research

In this chapter, the author summarizes important points in the new generation biomimetics research, paying due consideration to the examples of success in Europe.

4-1 Point 1: Evolution and Adaptation of Living Things Provide Good Models for Material Design: Diversity of Living Things Translates into Diversity in Material Designs

Professor S. Gorb at Kiel University (a natural historian and one of the leaders in "Bio-tribology"[34]) gave, in his book Attachment Devices of Insect Cuticle, a systematic and comprehensive description of the adhesion mechanism of insects' legs in line with evolutional grouping. The book makes it clear that the attachment mechanisms could be classified into several categories: those that do not require secretion of sticky substances (van der Waals type such as a gecko), those that use nail-like hooking structure, and so forth. The book also makes clear that what attachment mechanism an insect selects does not depend on the evolutional lineage of the insect, but is largely determined through its adaptation processes to the environment to which it is exposed. These discussions indicate that the manifold of attachment mechanisms of insects was brought about through the long passage of evolution and adaption. In line with this way of thinking, a systematic classification of relations between the structure and mechanism required to actuate a function could pave the way into the material design just to the purpose. Learning the evolutionary struggles between plants and insects, as described in the previous section, is expected to open the way for a broad spectrum of material designs.

[NOTE 6] MPI:Max Planck Institute
[NOTE 7] CAESAR:Center of Advanced European Studies And Research
[NOTE 8] CILIA:Customized Intelligent Life-Inspired Arrays

4-2 Point 2: Compilation of Biological Resources into a Database is the Key

Compilation of a database that contains information regarding the structure-function correlations of living things from the viewpoint of taxonomy would provide a guideline to the biomimetic material designs capable of coping with a variety of applications. In other word, an effective utilization of the diverse bio-inventory is the key to bring diversity into material research. As evidenced by the effort of Professor A. Parker et al at London's Natural History Museum (i.e., "Compilation of database to provide a guideline in photonics materials design"), systematic accumulation of structure-function correlations in natural history is a very important contribution and the accomplishment should be made available to the researchers. Professor S. Gorb also noted in the preface to his book Attachment Devices of Insect Cuticle, "the fact that the observation of surface structure of living things became widely available owing to SEM (Scanning Electron Microscopy) was the driving force for the dramatic development in this field." The research organization that undertakes systematic and comprehensive observation of the surfaces of living things on the microscopic level will surely play an important role in the future biomimetics research. In the United States, compilations of databases such as "Nature's 100 Best" and "Biomimicry Taxonomy" are being contemplated.

4-3 Point 3: Win-win Collaboration among Biology, Natural History, and Material Science Is Essential

Gathering knowledge on nano- /micro-structures of living things and the underlying relations of how these structures lead to a manifestation of a function is one of the major research challenges for biology, especially for morphology and embryology. As exemplified in the success stories in European biomimetics research, an important thing for material science is to verify and recreate the working principle of the findings in biology, and yet another important thing is to feed back the results to biology. The bridging of fundamental and applied sciences and the collaboration among dissimilar disciplines shed new light on biological specimens (natural historical resource) and bestowed them with engineering values. This approach also enables the feedback of engineering knowledge to help elucidate the biological mechanism leading to the manifestation of functions. This is a win-win relationship brought about by collaboration among dissimilar disciplines, and the key aspects to achieve this are for a biologist to have sophistication that does not alienate him from mathematical sciences, and for a material scientist to have a lively curiosity about biology.

4-4 Point 4: Design of Energy-saving Materials Should Learn from the Multifunctionality and Environmental Adaptability of Living Things

The new generation biomimetic materials are characterized by their hierarchical structures that range in scale from nanometer to micrometers, and mimicking the mechanisms inherent to living things to actualize the desired functions. These hierarchical structures can exhibit water-repellent property in one aspect and anti-reflective property in another. Professor Barthlott et al refer to the multifunctionality of the surface of living things having such a hierarchical structure.[35]

For example, the moth-eye structure is found not only on a moth but also on many other insects. The water-repellent complex eye is considered to save the smaller insects, such as a mosquito, from drowning in falling raindrops. The wing surface of the Morpho is covered by scales with a hierarchical structure that gives rise to characteristic structure color, and the structure also endows the insect with water-repellent property. Professor Lei Jiang et al at the Chinese Academy of Science found that the wing shows repellency in the directions from the center of the wing to the outer edge, and adsorptive property in the reverse directions. The direction that the wing repels water drops coincides with the airflow created when the butterfly flutters its wings, indicating that the directional property may endow it with a self-cleaning function: the attached water drops are driven from the center to the outer edge, eliminating surface fouling.

The water-repellent property of surface nano- and microstructures is also found in the transparent wings of a cicada. Transparent wings make them hard to distinguish from the surroundings. The chestnut tiger butterfly (Parantica sita), known to make a long-distance journey, has partially transparent wings. On the other hand, Parnassius glacialis, although it is not a long-distance flyer, also has transparent wings. Detailed comparison of the wing surface microstructures of these two butterflies revealed that the transparent portion of a chestnut tiger butterfly's wing has an ordered array, although low in density, of scales exhibiting high levels of water repellency, and Parnassius glacialis does not have such an ordered array of scales, resulting in weak water-repellency. The diversity in the forms of water-repellency and optical properties manifestation is considered to be the result of evolution and adaptation processes.[36]

Recently, a proposal was made to utilize the multifunctionality of biomimetic surface structures (water-repellency, self-cleaning, anti-reflection, transparency, etc.) to solar cells. In the background of the variety of functions contained on the surface of living things may lie a hidden "energy-saving" design principle. A thorough review of the structures, functions, and behaviors of living things, from a viewpoint of environmental adaptability and energy conservation, will be necessary when an attempt is made to design a new material.

4-5 Point 5: Collaboration between Material and Mechanical Disciplines Is Highly Desirable

Collaboration between material- and mechanical biomimetics is also an important aspect. Current alienation of these areas seems to have been exerting a disadvantageous effect. In the research on sharkskin riblets, collaboration with microbiologists constituted an essential aspect from the viewpoint of anti-fouling, and collaboration with fluid dynamics researchers was also an integral aspect in view of friction reduction.

Water drop manipulation using a water-repellent material also presents research themes applicable to a variety of areas including MEMS and combinatorial chemistry. Especially in the research area of lab-on-a-chip, the newly emerging digital microfluidics technology requires the technique and devices that enable water drop manipulation. The phenomena called electrowetting-on-dielectric (EWD) is mainly used for water drop manipulation. EWD makes use of the finding that the contact angle of a water drop placed on a hydrophobic substrate decreases upon application of an electric field. The ant cow (aphid), cohabitant with ants, knows how to handle a water drop in masterly poise; this may provide a useful hint for a biomimetics device design. The ant cow (aphid) secretes a stable liquid drop (called a liquid marble), thus preventing itself from drowning in the liquid inside the nest.[37] On the other hand, research that uses a non-EWD method for liquid drop manipulation has been underway. Observation of the phalarope revealed that the bird could move water upward to its mouth, defying gravity, using the open-close movement of its bill and surface tension of water. This finding indicates a potential application to reduce the resistance of the flow of liquid inside a pipe.[38] The development of MEMS chips that bases a flow passage on a new operational principle is expected. A type of beetle in Namib Desert is known to collect water from mist drops. In contrast, some types of cockroaches in the desert are believed to be able to adsorb water drops around their mouths even in humid conditions below saturation vapor.[39] These findings may provide useful hints for device designs that enable water drop manipulation in condensation/evaporation processes without consuming energy.

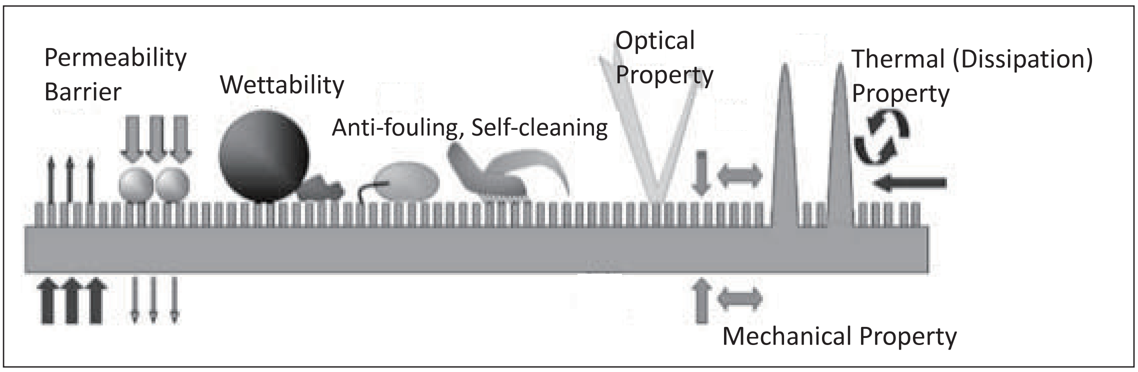

Figure 8 : Multifunctionality of Biological Surfaces

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4-6 Point 6: Formation of Self-organized Hierarchical Structure in Living Things Presents Valuable Clues for the Innovation of Manufacturing Technology

The new generation biomimetics research has a potential for bringing about an innovation in manufacturing technologies. Professor J. Vincent at Bath University, a biologist and one of the leaders in British biomimetics research, used a problem-solving method called TRIZ to conduct a comparative analysis of the elements of which a biological entity is composed and those used in an artificially constructed entity by means of industrial techniques. He concluded that, while living things make efficient use of "information," "space," and "structure" for their structure formation, the structure formation by means of conventional industrial techniques depends largely on "energy" and "materials."[40] Living things create information containing molecules such as DNA and proteins from very common elements such as carbon, oxygen, and nitrogen; these molecules in turn form structures such as a membrane and organelle, and the structural development proceeds further into a hierarchical formation of cells, tissues, and organs. On the other hand, industrial products such as the high-speed electric circuit use rare elements such as gallium and arsenic, and hack the raw materials into pieces using such technology as lithography accompanied by the consumption of enormous amounts of energy.

The structure formation processes in living things consists of a complex combination of chemical reactions governed by the program inscribed in the genes, where the self-assembly of molecules and self-organization of these molecular assemblies function quite effectively. The living things create their peculiar structures and bring a manifold of functions to life using neither the lithography nor petroleum. Professor Vincent's analysis suggests the possibility of new production technologies with a lesser degree of dependence on energy and materials.

In many cases of the development of new generation biomimetic materials, the "initial model" is manufactured using some of the nanotechnologies (e.g., electron beam drawing, lithography) for principle verification. In subsequent stages where the move to commercialization is in view, methods for efficient and economic production are required. A search for production technologies inspired by living things is needed, where the variety of techniques used in nanotechnology must be reviewed from a comprehensive point of view.[41] These include molding technology (e.g., nanoimprinting), patterning technology (e.g., ink-jet printing), crystal growth technology, application of self-assembly phenomena (e.g., block copolymer lithography, micro contact printing), and application of self-organization phenomena (e.g., dissipative structures). It seems unlikely that chemical reaction processes alone produce structured materials, but future incorporation of physical processes such as self-assembly and self-organization has the potential to produce highly structured materials.

Putting together the discussions so far, we can conclude that biomimetics has a potential to bring about a paradigm shift in industrial technologies. In conventional industrial technology, a superhydrophobic surface is obtained through the use of fluorine coating. The lotus leaves, in contrast, use organic material (wax-like secretion) and micro/nanostructure to realize a superhydrophobic surface. We use compound semiconductors to produce a highly sensitive infrared sensor, and a jewel beetle detects a fire from far away by using volume expansion of a liquid. Living things have realized equal or superior functionalities to man-made equivalents using completely different mechanisms. As Professor Vincent indicated, living things are able to create nano/microstructure without resorting to lithography. It is apparent that the living things possess a scheme of production techniques and system design that are quite different from the ones that we have cultivated since the industrial revolution. The new trend of biomimetics research involves a paradigm shift in modeling and fabrication techniques of materials and system designs. This new line of thinking seems to have already established its place in Europe and the United States as a policy concern toward the realization of sustainable society where such issues as the environment, energy, and natural resources must be addressed.

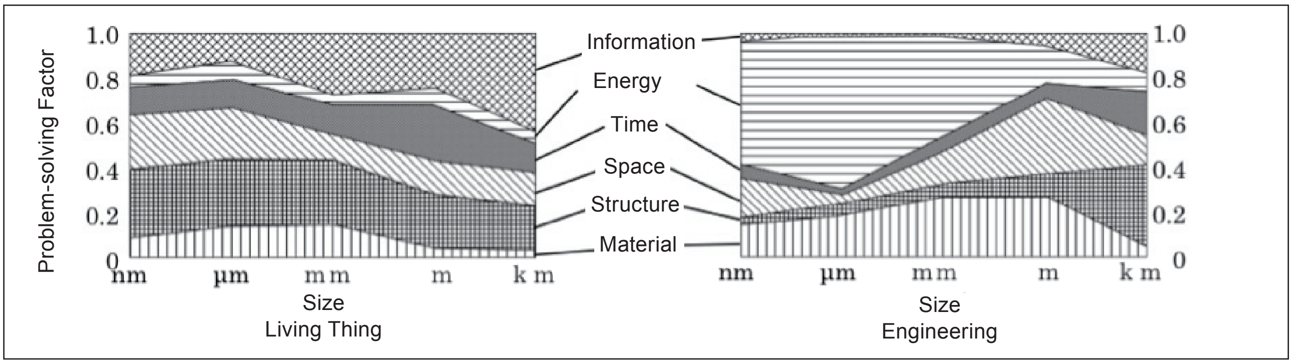

Figure 9 : Comparison of Manufacturing Method: Living Thing vs. Engineering (Analysis by BioTRIZ)

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5 The Approaches Employed in Advanced Countries

5-1 United Kingdom: Perception and Approach

In January 2007, the then Department of Trade and Industry (DTI) of the U.K. compiled a report called "Biomimetics: strategies for product design inspired by nature. A mission to the Netherlands and Germany." This report, compiled by DTI Global Watch Mission, described the potential contributions of biomimetics to the industrial arena in the U.K. According to the report, biomimetic research is being actively taken up in the U.K., Germany, the Netherlands, and the United States; among these countries, Germany is one step ahead of others in systematic integration of basic research and industrial applications. In the Netherlands, several advanced research organizations and enterprises have applied the biomimetics concept to product developments and designs, but as the report pointed out, they lack collaborative links among these individual research and development groups.

A network called "BIONIS",[NOTE 9] established in the U.K. in 2002, with core members consisting of the enterprises and universities in the U.K., issues newsletters transmitting topics in biomimetics and conference information internationally. Well-established links have been in place in the U.K. between fundamental research and prototyping, but it seems that the passage toward commercialization has not yet been well implemented. In the same light, in a report focused on "Multifunctional Materials" compiled by DTI's Material Innovation & Growth Team in 2006, the biomimetic material was taken up as one of the areas of future importance for the U.K., in addition to composite materials, coating materials, and nanostructure materials.

5-2 Germany

As mentioned above, Germany is acclaimed by the U.K. to have well-established research networks, and its new generation biomimetic research is characterized by a clear emphasis on biology. The "National Strategy on Biological Diversity" (2007) carried out under the initiative of the German government includes a section titled "Biological diversity and its innovation potential"; and it introduced such accomplishments as the lotus effect, gecko tape, and the jewel beetle's infrared sensor as potential technical innovation enablers. In COP9 (The 9th meeting of the Conference of the Parties of Convention on Biological Diversity) held in Bonn in 2008, the government of the Federal Republic of Germany initiated "Biodiversity in Good Company" and called for private enterprises to get involved in the activities of the biodiversity convention, as it has a significant impact on business activities, including the procurement of raw materials and manufacturing procedures.

In Germany, BIOKON[NOTE 10] has shown a good track record in market development, organization, and transfer of knowledge. BIOKON is the network established in 2001 under the auspices of, and funded by the Federal Government of Germany for industry-academic-government collaboration among 28 research organizations. BIOKON is characterized by its embedded design to enable organization of three important links in biomimetics: biology-engineering collaboration, collaboration among dissimilar engineering fields, and business-academia collaboration. Since 2009, the network has transformed itself into "BIOKON International," funded by the monetary support of more than three million euro from the Ministry of Education and Research of Germany, aiming to become an international network in the future. Among the eight board members, four come from France, Sweden, the Netherlands, and the U.K. With an aim of becoming independent from the government starting in 2012, it will host, as mentioned at the beginning of this article, the world's first "International Industrial Convention on Biomimetics" in 2011. As just described, the German government is proactively promoting biomimetics, eliminating vertically divided administrative functions, and the Federal Ministry of Economics and Technology devoted a significant portion of its white paper to this subject.[42]

5-3 Other European Countries

In FP7, the European Union has been pushing along biomimetics-related programs in many fields such as information and telecommunication, energy, and medicine,[43] as well as anti-fouling.[11] The white paper of the GENNESYS[NOTE 11] Initiative (Grand European Initiative on Nanoscience and Nanotechnology using Neutron-and Synchrotron Radiation Sources) devoted a significant portion of chapter three to Biomimetic nanomaterials. In Austria, the Federal Ministry for Transport, Innovation and Technology has been gearing up for the formation of academia-business enterprise networks in such a variety of fields as machinery, material, and biology.[44] In Sweden, a financing company (Swedish Biomimetics 3000®) specially designed to support commercialization efforts of biomimetics research has been established.[45]

5-4 United States

The white paper of the National Academy (U.S.), as mentioned at the beginning of this article, stated that, as one of the proposals relating to "Next Generation Bioinspired Materials," it is a challenge for scientific understanding "to select a wide range of biological multi-functional systems that provide an inspiration for the design of advanced materials." J. Benyus, the advocator of Biomimicry, established an incorporated nonprofit organization ("Biomimicry Institute") and a consulting firm ("Biomimicry Guild"), and opened a freely accessible database called "Biomimicry Taxonomy" at the website "Ask Nature", providing a list of tips useful for application of biodiversity to a variety of areas in science and technology. He also hosts the "Biomimicry and Design Workshop" regularly to transmit relevant information.

[NOTE 9] BIONIS: The Biomimetics Network for Industrial Sustainability
[NOTE 10] BIOKON: Bionics Competence Network
[NOTE 11] GENNESYS: Grand European Initiative on Nanoscience and Nanotechnology

6 The Approaches Employed in Japan: Challenges and Proposals

6-1 The Approaches Employed in Japan

As shown in Table 1, books and journals have been published in Japan relating to nature technology and biomimetics since the turn of the century, and surveys have been carried out (mainly by the Ministry of Economy, Trade and Industry) on establishing biomimetics policies. The Ministry of Education, Culture, Sports, Science and Technology adopted, in its "21st Century Center of Excellence (21st Century COE)" project, several related subjects as major graduate education programs, including biomimetic manufacturing (engineering) and novel applications of biological resources (agriculture). Several international conferences on these areas have been held under the initiative of Japanese researchers. Several technologies (e.g., water-repellent materials/paints, optical films with moth-eye structure) have already been put into practical use in Japan, and the biomimetic technology has been progressively attracting interest from business enterprises that are searching for new material designs and innovative manufacturing techniques.

6-2 Japan-Europe Comparison in New Generation Biomimetics Research and Development

The new trend in biomimetics is highly expected to go global, since they have the potential to sprout new technological innovations promoting new systems of science and technology that are capable of addressing the problems of modern society (i.e., energy, environment, and resource). As evidenced by the success stories in Europe and the United States introduced in this article, the collaboration between dissimilar fields in engineering and biology is integral to achieving such objectives. In the backdrops of highly active and original biomimetics research and development in Europe and the United States, a cultural factor that precludes vertical segmentation of science and technology seems to be taking effect. To further promote collaborations among dissimilar areas, the German government is practicing administrative

Table 1 : Surveys, Research Projects, and Books Related to Biomimetics in Japan

Survey	The survey conducted by the Tohoku Bureau of Economy, Trade and Industry "Survey on Industrial Pollution Prevention Technologies and Their Business Feasibility: In Relation to Nature Technologies" "Survey on Monozukuri Technologies That Mimic Biofunctions," NEDO, 2007 "Survey on the Next Generation Biomimetic Materials," NEDO, 2009
Research Project	"Creation of Nature-Guided Materials Processing," Nagoya University 21st Century COE Program, 2002 "Innovative Food and Environmental Studies pioneered by Entomomimetic Sciences," Kyoto University 21st Century COE Program, 2004
Concerns in Business Sector	Aid funds for "Monozukuri Forum Inspired by Nature," "Aid for Monozukuri Researches Inspired by Nature," Sekisui Chemical Co., Ltd. "Challenge to 2030: Next Generation Industrial Technologies" Bio-mimicry, Parts 1 and 2, Nikkei Sangyo Shinbun, February 9–10, 2010 "Technology Watch," Environment Friendly Technologies Inspired by Nature, NIKKEI, January 23, 2010 "Biodiversity for Company Management," Parts 1, 2, and 3, NIKKEI, May 4–5, 7, 2010 "Pictorial Presentation: Japanese Economy 2010," Amazingly Efficient Monozukuri Inspired by Living Things, Economist Special Issue
International Conference	International Conference on "Biomimetics Material Processing," 2001–2009 International Symposium on "Engineering Neo-Biomimetics," 2009
Learned Book	"Biomimetics Handbook," 2000; "New Development of Biomimetics," 2002; "'Fiber': Super Biomimetics," 2006; "Plantmimetics," 2006; "New Generation Nanomaterials Inspired by Insects," 2008; "Insect Mimetics," 2008; "Future Created by Insectology," 2009
Introductory Book	"Snail Teaches Us: Ultimate Monozukuri Inspired by Nature," 2004; "Monozukuri Inspired by Nature," 2005; "Power of Insects," 2006; "Sophisticated Technology Inspired by Nature," 2009; "The Earth Teaches Us: Miraculous Technology," 2010

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Table 2 : Japan-Europe Comparison in the Next Generation Biomimetics Research
(○ : Good, △ : Needs improvements, × : Insufficient)

	Europe		Japan	
Linkage among Material Science, Biology, and Natural History	○	Variety of good linkages under the initiative of biologists; Nanotechnology is integral Collaboration required for budget allocation	×	Linkage is only seen between molecular-level biology and material science.
Intra-Engineering Linkage (material and mechanics)	○	Concentrated budget allocation on collaborative projects involving dissimilar areas	×	Next to no linkage between material and mechanics/robotics domain
Academia-Industry Alliance	△	German government actively supports alliance. Quickest way is to establish a venture. Large U.K. enterprises tend to keep a "wait and see" position.	△	Catch-up effort to European accomplishment depends largely on private sector.
Educational Program	○	Collaborations in doctoral programs among plural of universities (Germany). Variety of areas are involved.	△	Improvement effort such as 21COE. Programs are contained in single area/ university.
Museum Involvement	○	Database compilation of inventories (specimen collection)	×	Lack of contact with engineering (material science and mechanics)
Network Formation (academia-industry, between dissimilar areas)	○	Active network formation (especially in Germany and the U.K.); German government supports proactively (e.g., European Consortium)	×	Nil
Budget	○	In addition to national budget, EU sets priority subject in FP6, FP7.	×	General external funding
Policy Involvement	○	Each government conducts independent survey. Compilation of white papers in various academic domains and proactive policy proposals.	△	Surveys are conducted mainly by METI and NEDO. Survey almost limited to near-industrialization subjects. Next to no contribution from biologists.

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guidelines that favor, in terms of funding, only the researches involving joint efforts among dissimilar fields. If we try to extract the challenges Japan must face in the new generation biomimetics research, comparison with the situation in Europe could provide meaningful findings.

Table 2 summarizes the comparison results between Japan and Europe in terms of collaborations among dissimilar fields, university-industry relations, educational programs, budget allocation, and policy-making surveys. In Europe, the problems presented from biology have been proactively addressed in collaboration with other scientific fields (e.g., nanotechnology), and, as can bee seen from the table, human resource cultivation and network formation have been pushed forward as elements of policy framework involving even such entities as museums, as well as various industrial sectors. Unfortunately, in contrast to the situation in Europe, collaborative efforts across dissimilar fields have not been promoted enough in favor of the projects that fit in the vertically segmented system. Admitting that Japan is not very good at forging a collaboration among dissimilar fields and creating a fusion area, it seems apparent that any effort done by one single sector in Japan to catch up and follow up on the successes of biomimetics researches in Europe and the United States will not dissolve Japan's current lagging position.

6-3 Problems in Japan and Their Background

The reasons for the new generation biomimetics research—an accomplishment of collaborative effort between dissimilar fields (i.e., biology and nanotechnology)—have continuously been rough going in Japan. Japan has had a tradition and accomplishments in Biomimetic Chemistry, which can be considered to be molecular biomimetics, a part of it giving birth to a trend of biomaterial research. This trend has grown up to now in the area of medical applications, leading to successful collaboration between material science and medicine. Behind the successful medicine-engineering collaboration in Japan lies the fact that biomaterial researchers had a working knowledge of medicine and they also had a good understanding of the challenges and issues at the medical front. A substantial academic society and educational system also contributed to these successes. On the other hand, in supramolecule science, which is considered to be the natural successor to molecular biomimetic researches and is the central research area for raising the level of nanotechnology addressing atoms, molecules, and molecular assemblies, there has been difficulty in finding suitable research areas to collaborate with (i.e., limited to areas where similar size of objects are handled). The research area that handles the size range from nanometers to micrometers, and even to millimeters—the territory of taxonomy and morphology that triggered the rise of the next generation biomimetics in Europe—was not the area of specialty of the supramolecule science in Japan. As a result, hardly any attempt was made to collaborate with such dissimilar areas as entomology, zoology, and botany. This situation caused the material biomimetics research in Japan to start by importing biomimetic designs of new materials from the papers published in Europe and the United States. In such a stage, neither the knowledge of botanists nor collaboration with them is required. The problem on the side of material science lies in the fact that researchers did not find merit in searching for clues for a new material design from structures and functions of living things through contact with biologists alone. They resigned themselves to catching up with the ideas found in Europe and the United States. The origin of this problem can be traced back to the lack of biological knowledge on the side of Japanese material scientists, and they were reluctant to engage in people-to-people exchanges. In marked contrast to this, the biomaterial researchers were eager to acquire medical knowledge. They proactively organized academic societies and cultivated human resources, resulting in a fruitful medicine-engineering collaboration.

On the side of biology, the origins of the problems can be sought in the extremely vertically compartmentalized learning system and academic organizations. Segmentation of a learning system is much more far-reaching in biology than in engineering disciplines. Taking insect research as an example, there are a variety of approaches, depending on their standpoints, including taxonomy, agronomics (anti-bug point of view), physiology, and developmental biology: intercommunion among these researchers is not necessarily frequent. In the area of biomimetics, the main task assigned to biology is to elucidate the nano/micro structures of living things and their biological functions. In Europe, taxonomists and morphologists have played leading roles in the next generation biomimetics research. In Japan, in stark contrast to Europe, no biomimetics-related research has been reported in the fields of taxonomy, morphology, and embryology. Agricultural entomology has developed as an applied science, as its main research objectives have been the silkworm and its destructive insects. As a theme in the 21st Century COE (see Table 1), the Agricultural Department of Kyoto University put forward the concept of "entomomimetics" as an aspect of "Insect-inspired science." In line with this concept, attempts have been made to develop inset robots in collaboration with mechanical biomimetics. As Professor Kenji Fujizaki, the representative of the group, started an exchange with Professor S. Gorb at Kiel University, the leader in next generation biomimetics research in Germany, the interest on material biomimetics has been spreading among the applied entomology community.

"Insect Mimetics" published in 2008 is the first full-fledged handbook on this subject in Japan and was compiled mainly through the efforts of animal physiologists, wherein many researches carried out by European entomologists and animal physiologists (including Professor J. Vincent's accomplishments) are introduced. The chief editor Tateo Shimozawa (Professor Emeritus, Hokkaido University) is a physiologist with a background in electronic engineering, and his research on insect's sensory hairs, which introduced an engineering method in this area, was highly acclaimed in Europe and the United States. The results of his research are also known to help launch the project of Professor J. Casas et al (see the description in section 3-8). Although lagged behind Europe and the United States, the concept of biomimicry seemed to have germinated among the biologists who can consider the subject in view of engineering and agricultural applications. However, the "entomomimetics" in the agronomics community and the "insect mimetics" in physiology community are—in spite of the fact that they share challenges and awareness of the problems involved, and similar contacts with material science and mechanical engineering—undergoing development largely independent of each other and under the influence of the vertically compartmentalized academic system and scientific communities. As a result, in spite of the fact that the Japanese scientific community had the basis and potential to develop the next generation biomimetics research under biologists' initiative, these systematic and conventional problems presumably hindered it from developing into the new trend that is being seen in the European arena.

6-4 Challenges and Proposals

To construct a new technology system in Japan, which may be called "biomimetic engineering," characterized by the adoption of a "material and system design inspired by biofunctions" and "manufacturing technology inspired by bioprocesses," many issues must be addressed, including: (a) collaboration between engineering (material science, mechanical engineering, etc.) and natural science (biology, natural history); (b) collaboration among dissimilar areas inside biology and engineering, (c) a rapid establishment of academia-industrial alliance, and to promote these measures, (d) a system for human resource cultivation and education in view of reducing barriers separating the dissimilar disciplines. For rapid promotion and activation of collaboration among dissimilar areas, the establishment of a center facility that functions as the "biomimetic initiative" (the possible title may be "the biomimetic center for cross-governmental collaboration") may prove effective. This facility should organize comprehensive collaborative research entities cutting across the national agencies (National Institute for Materials Science, National Institute of Advanced Industrial Science and Technology, National Institute of Agrobiological Sciences, RIKEN, National Institute for Environmental Studies, National Museum of Nature and Science, etc.), the natural history museums managed by local authorities, universities, and other relevant facilities. It should also propose, as policy challenges, the launch of academic-industrial alliance projects and collaborative research programs that fuses dissimilar academic disciplines. Furthermore, the following activities should be promoted concurrently: human resource cultivation programs involving multiple academic societies in different academic domains, scientific education programs and scientific enlightenment activities as a joint effort among science museums, universities and academic societies, and recurrent education for technologists.

6-4-1 Roles of Museums

The role of museums, with a vast amount of biological specimen, or biological resources information, is essential. It is an urgent task to create a comprehensive biomimetic database through consolidation and organization of the museums' inventories, whereby such approaches as data mining and "knowledge structuring" should be utilized. The database enables researchers to find engineering values in the collected specimen, which is useful for both taxonomy and morphology from an academic point of view as well. In fact, the museums in Europe are actively practicing cooperative activities and academic-industrial collaborations with material/device researchers based on database information (e.g., electron micrographs). The procedure of compiling a database from biological resources inventory from an engineering viewpoint provides a platform for engineers and biologists to know each other. This is exactly the process of transforming a "specimen" into a "treasure," from which the researchers could find an objective of cooperative research. Diversity of living things is reflected in the diversity of new materials, because the latter is designed based on the concept obtained by mimicking the former.

6-4-2 Creation of New Academic Research Domain through Collaboration of Dissimilar Areas

Living things form hierarchical structures (from nano-, to micro-, and even to macro-scale) autonomously. The objective of the new generation biomimetics research is to elucidate the structures (the scale of which ranges from nanometers to micrometers) and their functions, as well as the mechanisms through which the structure manifests its function. This is a different approach from that employed by molecular biology; and even nanotechnology did not use the approach in the process of its development. The biomimetics research is exactly the deed of filling the gap between the nano- and micro-domain, and the linkage between molecular nanotechnology and microstructure of living things will lead to a fusion of life science and engineering. In turn, the accomplishments of biomimetics research will be fed back to development biology and morphology. This is the essence of the new generation biomimetics research that makes it worthwhile to be ranked as a new academic domain.

6-4-3 Creation of Academic-Industrial Alliance Projects for Practical Realization

The discovery of the lotus effect is a success story that symbolizes biomimetics research and development in Germany, and the German government is helping form an academic-industrial alliance network (BIKON) as a policy concern. This also indicates that, even in Europe, promotion of academic-industrial alliance in this field needs assistance from the government. Although the situation in Japan is one lap behind, a political leverage for such network formation could have an enough potential to work miracles.

In addition to promoting academic collaboration between biology and engineering, an academic-industrial collaboration should be organized into a joint-research consortium under a political initiative involving the group of companies that can address energy, environment, and resource issues, and the challenges and projects for the academia-business collaboration entity should be set. For example, incorporation of the moth-eye structure into solar cells facilitates more efficient energy production; application of low-friction materials inspired by the insect's legs to automobiles helps achieve higher efficiency in energy usage; and the development of bottom-up nanotechnology based on self-assembly and self-organization toward its technologising will realize manufacturing processes that consume much less energy. These challenges, at once, represent greater political challenges to be overcome toward the realization of a sustainable society.

6-4-4 Education and Human Resource Cultivation

The cultivation of engineering researchers with an interest and understanding in biology is integral to the future development of biomimetics research. As was described in 3-6, Germany has a COE program (called BIONIC Graduate) targeted at doctoral course education. This program works in conjunction with the consortium for the technologies mimicking the sensory hair of insects, and the researchers who specialize in different areas of expertise, from different universities, carry out cross-border training to graduate students. An incorporation of biology into engineering education is essential for the students to find engineering values in the structures and functions of living things. Through biomimetics research, it is also important to enhance science education in elementary and middle schools and recurrent education of corporate researchers, where the enlightenment and publicity capability of museums will play an essential role.

Behind the reasons that caused Japan to fail to join the trend toward new generation biomimetics research seems to lie the educational and cultural background of this country: the current educational system is producing biologists who have an aversion to physics and mathematics, engineers who dislike memorizing, and students who enter medical departments without having learned biology in high school. Department organization in universities is still subject to the influence of a vertically compartmentalized educational system that started in Meiji-Restoration, and this has an effect on elementary and middle school education, and especially on science education. In addition, a highly homogeneous organization of academic societies may be an element to producing a passive culture toward alliance among dissimilar areas. To try to free Japan from catching up with Europe and the United States, and to demodernize toward an advanced scientific and technological powerhouse, it is important to cultivate human resources who have the capacity to "set a problem to produce a challenge."[46] Especially, toxonomists with an understanding of physics, and engineers who are familiar with insects are required in future.

Acknowledgement

Through the writing of this article, the following researchers offered helpful discussions and guidance. The author extends sincere thanks to: Mr. Masanori Tomokuni (manager of the Zoological department, National Museum of Nature and Science), Professor Kenji Hujizaki (Agronomical department, Kyoto University), Mr. Tateo Shimozawa (Professor Emeritus, Hokkaido University), Mr. Hisashi Horishige (section manager, Historical Museum of Hokkaido), Professor Takahiko Hariyama (Hamamatsu University School of Medicine), and Professor Jun Takahara (Institute of Materials Chemistry and Engineering, Kyushu University).

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(Original Japanese version: published in May 2010)